1916; August 16–18. 1919; June 16–18, July 7–10, September 3–4.

A close study of local conditious on June 22–24, 1919, suggested that marked local convection might temporarily divert the cirrus from a normal path. Active convection during the forenoon of June 22, as shown by highly developed cumuli, was followed, during the afternoon, by a succession of thunderstorms that apparently formed northeast of the station and developed westward and southwestward. True cirrus moved from the east at 7 a. m., 11 a. m., and 12 noon, and cirro-stratus from the southeast at 3.45 p. m., 4.45 p. m., and 7 p. m. Thunderstorm conditions continued through the 23d. On that day the cirro stratus moved from the southeast at 7 a. m., 3.15 p. m., and 6 p. m. Active convection ceased by the morning of the 24th and the clouds returned to their normal drift.

Similar conditions appear to have existed on September 4, 1909, June 23, 1910, June 22, 1911, July 17, 1912, July 15, 1916, and July 28, 1916, but the entire series of observations does not furnish sufficient data for a productive investigation of this feature.

THE WEST INDIA HURRICANE OF SEPTEMBER, 1919, IN THE LIGHT OF SOUNDING OBSERVATIONS.

By R. HANSON WEIGHTMAN, Meteorologist.

[Dated: Weather Bureau, Washington, Dec. 3, 1919.]

The hurricane of September, 1919, is the first well-developed storm of tropical origin in connection with which sounding observations of wind directions and speeds in the free air are available for study purposes. In 1906 and 1907 while Rotch and de Bort were conducting sounding balloon and kite work[1] in the south-eastern portion of the North Atlantic Ocean several disturbances of minor importance occurred in the West Indies but, unfortunately, many hundred miles away from the point where observations were being made. Again in the early part of August, 1918, a disturbance of intense character but of very limited extent developed in the Gulf of Mexico and passed inland west of New Orleans during the 6th. The nearest point to the storm at which sounding observations are available is Fort Sill, Okla., about 500 miles distant. On the mornings of the 5th and 6th at this station the winds up to the greatest elevation reached, the 2,000 meter level, were from the SW., 10 to 18 m. p. s., and at noon of the 6th they had backed to SSW. and decreased somewhat in velocity, seemingly unaffected in any way by the disturbance.

In the September, 1919, hurricane upper-air observations are available from three stations in Texas, two in Oklahoma, one in Georgia, and from nine or ten other stations outside of the Gulf States. The most complete series of observations from a point relatively near the hurricane center is from the Leesburg, Ga., station, the nearest point reached by the storm center, however, being about 500 miles. At the time the disturbance was approaching southern Texas, the sky over that region unfortunately became overcast for the most part, thereby preventing the making of observations at greater altitudes than 3.5 km. and in most cases under 2.

Perhaps the most interesting feature brought out by these observations is the rather sudden change in wind direction as shown by sounding balloons at Leesburg. For several days previous to September 5, the winds above 3 km. were from a westerly quarter while near the surface they were between north and east. On the 1st westerly winds were first encountered at the 2 km. level, on the 2d at the 3-km. level, on the 3d at 3-km., on the morning of the 4th they had descended to 2 km. and by evening had risen to 3.5 km. On the morning of the 5th they were first observed at the 4-km. level and by the afternoon of that date were not in evidence up to 11 km., the greatest altitude reached. So far as observations are available, no trace of westerly winds is found until the morning of the 12th, when they were encountered at an elevation of 6 km., and by the afternoon of that date they had descended to 4.5 km. This shift of the upper winds to W. and N. seems to have been of a temporary character, for on the 15th they were generally between ENE. and ESE. up to 11 km., and it was not until the 16th that they changed to steady westerly.

A current from the east was then fully established at Leesburg at all altitudes up to probably 10 km., at least, from the evening of the 5th to the morning of the 12th, a rather unusual occurrence, if we may judge from a casual inspection of the observations made during the two or three preceding months. In the lower strata, at least, this distribution of winds is consistent with the surface barometric distribution, for during the time of the prevalence of the easterly winds pressure was relatively high over the southern Appalachian region and the interior of the east Gulf States and relatively low to the southward. The persistence of the easterly winds in the upper layers, however, appears to be quite unusual. This easterly current is also in evidence up to the 5 km. level at the south Texas stations, i. e., Groesbeck, Ellington Field near Houston, and Kelly Field near San Antonio, from the 1st of the month until the time the hurricane crossed the Gulf coast about 50 miles south of Corpus Christi on the 14th. The highest levels shown by the observations do not exceed 5 km. except in two cases; one on the morning of the 5th at Kelly Field, showed winds between N. and NW. between 5 and 10 kilometers. This easterly current seems to have a rather well-marked limit, for the stations at Broken Arrow and Fort Sill, both in Oklahoma and less than 500 miles to the northward, showed a number of observations between the 5th and 10th of the month, in which the winds were from a westerly quadrant. Likewise, with the easterly winds observed at Leesburg, the northern boundary must have been quite well defined for the sounding observations at Washington about 750 miles distant show practically all winds from a westerly quarter. The southern limit of the easterly current is rather difficult to determine, but an examination of the cloud observations at Swan Island, Belize, and Bluefields shows that easterly winds prevailed in the cumulus level (about 2,000 meters) up to the 8th. During the 4th a minor disturbance passed over Santo Domingo, advanced northwestward to the west of Turks Island by the morning of the 5th, and from that point recurved to the northeastward. On the evening of the 6th after the passage of this disturbance the winds over Jamaica in the cumulus level were southerly, over Haiti southeasterly,

[1] Etude de l'atmosphère marine par sondages aériens; Atlantique moyen et région intertropicale. Par Mm. L. Teisserenc de Bort et Lawrence Rotch. Travaux Scientifiques de l'observatoire de Météorologie Dynamique de Trappes. Tome IV.

and over Porto Rico easterly (see fig. 1), and the wind at Turks Island had backed to the southeast, indicating the presence of a second disturbance to the southwest or westsouthwest of that point. Fig. 1 shows a circulation of considerable extent with S. to SE. winds on the south side and NE. winds on the northwest side, which is the earliest recognizable stage of the hurricane. Figs. 2, 3,

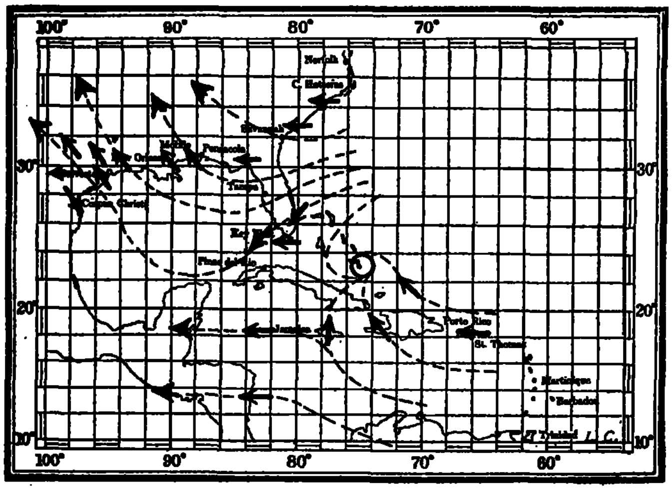

FIG. 1.—Instantaneous stream lines (2,000-m. level), p. m., Sept. 6, 1919.

and 4 show subsequent stages of the storm. The arrows indicate wind directions in the cumulus level (2,000 m.) as obtained from clouds and sounding observations. Instantaneous stream lines[2] have been drawn in order to bring out to the best advantage the existence of the countercurrents to the northwest and southeast of the area

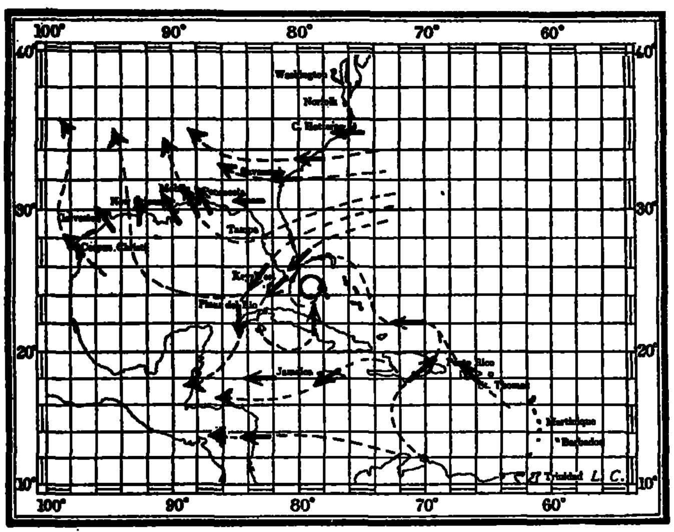

FIG. 2.—Instantaneous stream lines (2,000-m. level), p. m., Sept. 7, 1919.

where the storm developed. The small circles show the center of the hurricane.

On page 6 of MONTHLY WEATHER REVIEW, Supplement No. 4, Anticyclones of the United States and Their Average Movements, it is stated:

> Likewise in the late summer and early fall months of the Northern Hemisphere hurricanes occur in the doldrums, a region flanked on the north by the northeast trades and on the south by the southeast trades, which latter on crossing the Equator and passing to an appreciable north latitude are deflected to the right and become southwest winds.

[2] The Life History of Surface Air Currents. By W. N. Shaw and R. G. K. Lempfert. M. O. 174.

It would seem that the wind conditions depicted on fig. 1 are a good illustration of the principle stated in the above extract.

An inspection of the means of the velocities at Leesburg at the 2,500-, 3,000-, and 3,500-meter levels during the hurricane are shown in fig. 5. These levels were chosen for the reason that it was believed a mean of

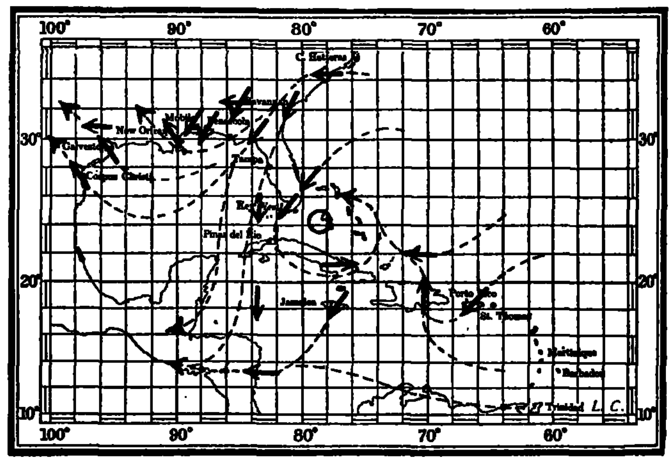

FIG. 3.—Instantaneous stream lines (2,000-m. level), p. m., Sept. 8, 1919.

them would be reasonably representative of the general air movement and secondly they were the highest levels at which a sufficient number of twice daily observations were available. It will be observed that winds were of small velocity, i. e., below 5 m. p. s. previous to the 6th and that from the evening of the 6th to the morning of the 10th they were greatest, averaging about 9 m. p. s., after

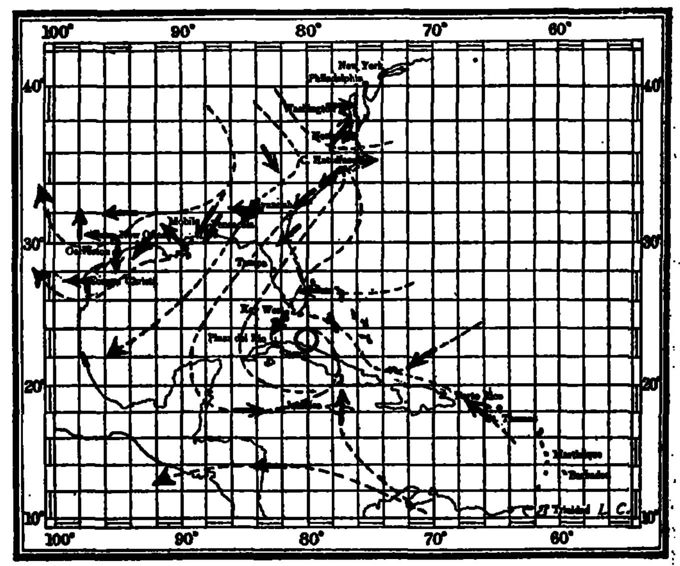

FIG. 4.—Instantaneous stream lines (2,000-m. level), p. m., Sept. 9, 1919.

which time they decreased to less than 6 m. p. s. At its inception the center of the hurricane was about 1,000 miles from the station and on the 10th it was about 500 miles distant. It is rather difficult to explain the fact that during the time the storm was nearest the station and while it was at its maximum development these wind velocities decreased to about half of what they were when the storm was approaching its nearest point and before it had attained full intensity. However, having in mind the countercurrent theory of storm development, it is interesting to note that the high velocities of these easterly and northeasterly winds—little is available to show directions and velocities south of the center—preceded the increase in intensity of the storm and that a short time after these currents decreased to normal velocities the storm did not further increase in intensity. The storm was able to maintain its destructive violence for about 5 days after the easterly winds at Leesburg had decreased to normal velocities, after which time it

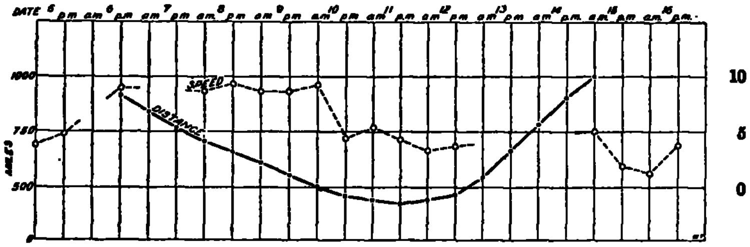

FIG. 5.—Distance of hurricane center from Leesburg, Ga. (solid lines) and mean of wind speeds at 2,500, 3,000, and 3,500 meter levels at Leesburg, Ga. (broken lines).

decreased in intensity. It is believed that, whatever be the cause of the high velocities noted, they were instrumental in causing the storm. The cause of the high easterly winds the writer is at a loss to explain. It has been suggested that the overflow of air from the storm may have had the effect of decreasing the barometric gradients aloft, thereby causing the winds to decrease as the storm approached the station. Observations of the vertical barometric gradients as obtained from the kite observations at Leesburg are somewhat meager. Observations

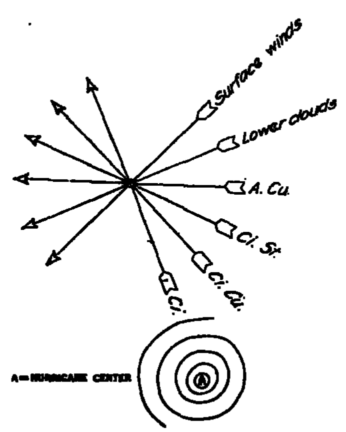

FIG. 6.—Direction of cloud movement with reference to direction of hurricane center.

are, however, available for the 3rd, 5th, 6th, 7th, 13th, and 14th but the gradients on those dates fail to explain the cause of marked increase in the wind velocities from the 6th to 10th and the decrease thereafter, the gradients between the surface and 1,000 meters, 1,000 to 2,000 and 2,000 to 3,000 being practically the same preceding, during, and subsequent to the increase in the winds.

It has been stated in connection with tropical storms that the direction of the winds at different elevations as evidenced by the movement of clouds, forms different angles with the line connecting the point of observation and the storm center.[3] The following extract from Mr. Boyer's paper gives the underlying principle of atmospheric circulation in and around hurricanes as enunciated by Father Vines.

As a rule the lower currents converge, forming with the bearings of the storm center a variable angle which is almost always greater than

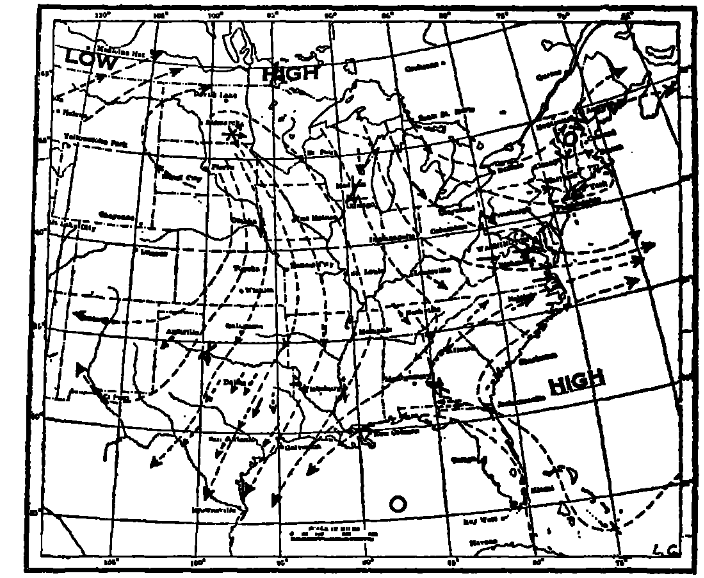

FIG. 7.—Instantaneous stream lines (2,000-m. level), p. m., Sept. 11, 1919.

a right angle. * * * The lower clouds in the interior of a hurricane fly ordinarily in directions perpendicular to the bearings of the center. * * * The cumulus (high) (alto-cumulus?), cirro-stratus, cirro-cumulus and the cirrus clouds that precede the hurricane generally diverge, that is to say their direction forms with the bearings of

FIG. 8.—Instantaneous stream lines (4,000-m. level), p. m., Sept. 11, 1919.

the center an angle less than 8 points (90°) with the very noticeable peculiarity that if different strata are observed it will be seen that the divergence increases with elevation.

Fig. 6 which appears in both papers referred to shows the relative directions at the different levels. To test the

[3] Atmospheric circulation in tropical cyclones, as shown by the movement of clouds H. B. Boyer, Washington, 1896. U. S. Weather Bureau publication, and West Indian Hurricanes, Benito Vines, Washington, 1898. U. S. Weather Bureau publication No. 168.

application of these principles to a storm in the Gulf of Mexico around which numerous observations are available, charts were prepared for several dates using the cloud observations and sounding observations, it being considered that certain kinds of cloud were representative of certain elevations and four levels were adopted as follows:

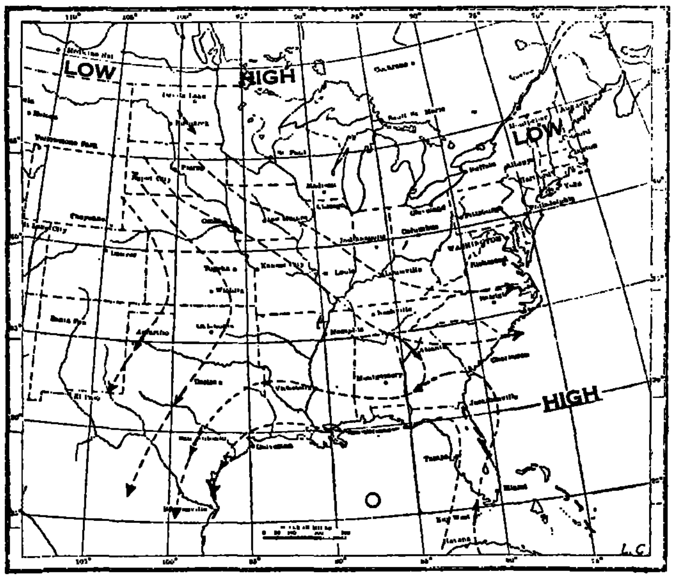

FIG. 9.—Instantaneous stream lines (6,500-m. level), p. m., Sept. 11, 1919.

Meters.	Cumulus.	Strato-cumulus.	Alto-cumulus.	Alto-stratus.	Cirro-cumulus.	Cirro-stratus.	Cirrus.
2,000	1,585	2,123					
4,000			3,656	4,572			
6,500					6,096	6,706	
8,500							8,534

FIG. 10.—Instantaneous stream lines (8,500-m. level), p. m., Sept. 11, 1919.

The afternoon sounding observations were used together with the clouds recorded at 8 p. m., 75th meridian time, and when clouds were not available at that observation those observed at noon were employed, the 8 p. m. and noon observations being separated by a nearly equal time interval from the sounding observations. The maps of September 11 are reproduced in figs. 7, 8, 9 and 10. From an inspection of these charts on which instantaneous stream lines have been drawn and on which the center of the hurricane is indicated by a small circle, it is apparent that the principles set out by Boyer and Vines are not entirely applicable to this storm, however well they may be adapted to conditions in the West Indies—nor do the charts for other days change this point of view. In this connection it is a fact that the winds at Leesburg on the morning of the 9th were NE. at every level from the surface up to 5 km. and NNE. at 6 km., the greatest reached, and on the afternoon of the 9th winds were NE. or ENE. up to 7 km., the highest level reached. This condition was also observed at Kelly Field on the afternoon of the 11th when the winds were NNE. from the 500-meter level up to 6 km. Again, at Broken Arrow on the 12th winds were NNE. up to 7 km. with the exception of two levels, namely, E. at 500 meters and NE. at 1,000. In other words, they had practically the same direction up to the limit of observations and were not observed to diverge with elevation.

It would further seem that these data are but another argument for setting aside the long cherished

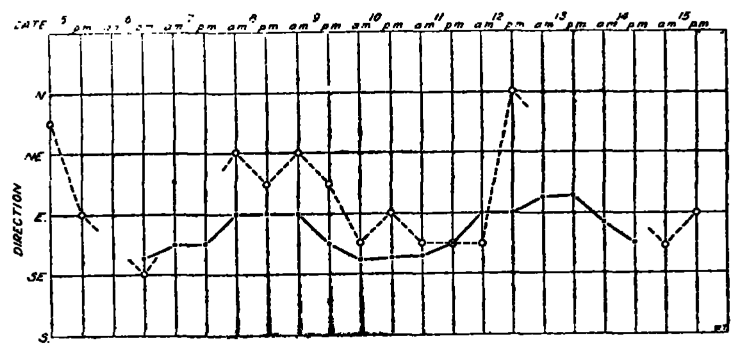

FIG. 11.—Direction of movement of hurricane (solid lines) and mean of wind directions at 2,500, 3,000, and 3,500 meters at Leesburg, Ga. (broken lines).

theory that in cyclones there is an outflow in the upper strata which is in effect anticyclonic.

Fig. 11 shows the wind direction at Leesburg, a mean being taken of the 2.5, 3.0, and 3.5 km.-levels, and the direction of movement of the storm center each 12 hours. It will be seen that they correspond in quite a marked degree, which would seem to indicate not necessarily that the storm was carried along in the drift of the easterly winds but rather that the storm passed westward along the southern boundary of the great easterly current.

The following extract from a paper by H. H. Hildebrandsson[4] refers to statements by Clement Ley concerning the movement of cyclones in the Northern Hemisphere is pertinent in this connection:

> However, if the steepest gradients are found to northwest, north or northeast of the center, it (the cyclone) most frequently remains motionless or moves (evidently slowly) in any direction, although a movement toward the west, which should then be found, is in reality relatively rare.

The movement of the September, 1919, storm was unusual in direction and in rate of movement, and, further, pressure was relatively high to the north of the center. The movement was unusual in that storms originating north of the Islands generally move north and northeastward, and the rate of movement was abnormally slow, in fact only about 200 miles a day, whereas the average for September storms approximated 250 miles a day, that is only about four-fifths the usual rate.

[4] MONTHLY WEATHER REVIEW, June, 1919, 47: 375.

INTENSE RAINSTORM OF OCTOBER 4, 1919, AT DUBUQUE, IOWA.

On October 4 Dubuque was again visited, for the second time during 1919,[1] by a rainstorm of great intensity. The fall within an hour (2.66 inches) has been exceeded since the beginning of record 46 years ago only by the storm of July 9, 1919, and probably by the storm of July 4–5, 1876. The storm of October 4 gave a total of 3.38 inches, as compared to a total of 3.87 inches on July 9. Rainfall was not remarkable on either date for "total" amount, but for intensity of fall within an hour.

The great downpour occurred between 3.13 p. m. and 4.39 p. m., 90th meridian time, and was preceded by and followed by light rain. Rainfall was excessive from 3.18 p. m. until 4.38 p. m., and accumulated amounts during this period were as follows:

	Inches.		Inches.
5 minutes	0.15	35 minutes	2.18
10 minutes	.35	40 minutes	2.33
15 minutes	.70	45 minutes	2.44
20 minutes	1.27	50 minutes	2.54
25 minutes	1.63	60 minutes	2.66
30 minutes	1.98	80 minutes	2.97

The following table gives the greatest amount of rainfall in 5, 10, 15, 30, 45, 60, and 120 minutes during the storm of October 4, as compared with the storm of July 9, 1919:

Greatest amount in—	Storm of July 9.	Storm of Oct. 4.
	Inches.	*Inches.*
5 minutes	0.80	0.59
10 minutes	1.20	.96
15 minutes	1.52	1.35
30 minutes	2.23	2.06
45 minutes	2.64	2.43
1 hour	2.70	2.66
2 hours	3.03	3.06

The storm of October 4 was more local in character than that of July 9, and the area of heavy rainfall did not extend to Union Park, where great damage resulted on July 9. Intense rainfall, however, fell over the entire city, causing great damage to brick pavements on waterway streets. The effects of the storm within the city limits were practically a repetition of what occurred on July 9.

The brick surface of Eighth, a steep waterway street, was again ripped off for several blocks. Seventeenth and Twenty-second Streets experienced similar damage as on Eighth, though much less steep. Seventeenth was not much damaged on July 9. Kaufmann Avenue was in process of repaving due to damage from the storm of July 9, and much of the new work was ruined as before, causing heavy loss to the contractor. East of Clay and north of Sixteenth a flat, residential section two or more blocks wide and more than a mile long became a temporary lake during the storm and scores of cellars in this section were flooded and considerable property damaged.

There was other damage of a less serious nature in various parts of the city. The bathing beach property at Eagle Point, for instance, was much damaged for the third time this season. Losses outside the city were not heavy. Four small county bridges were damaged or destroyed by freshets, the loss amounting to about $3,000.

The total loss from this storm is estimated at about $60,000, at least two-thirds of which amount was to city streets. Fortunately, in this storm no lives were lost, as on July 9.—*J. H. Spencer.*

[1] See MONTHLY WEATHER REVIEW, July, 1919, 47; 468.

SOME BROADER ASPECTS OF RAIN INTENSITIES IN RELATION TO STORM-SEWER DESIGN.

By ROBERT E. HORTON.

[Abstracted from Municipal and County Engineering, June-July, 1919, 4°, 12 pp., 16 figs.]

Owing to the large number of rainfall intensity formulæ which are used in various localities in storm-sewer design, the author was led to make a study of them, with special relation to the underlying physical and meteorological causes of excessive rainfall. After defining the terms "rainfall rate" and "rainfall intensity" and pointing out the distinction of the two terms, namely, that "rate" implies quantity per unit of time, whereas "intensity" implies a quantity in a given time interval, the author explains the notation employed in formulæ and gives the several types into which these formulæ have fallen. The mechanism of the thunderstorm is then discussed, together with the character of the rainfall rates of different types of storms, tropical rainfall, and the frequency curves of excessive rains in New York. The following are some of the conclusions:

1. Excessive rain intensities for short-time intervals mostly occur in thunderstorms, or in storms of the thunderstorm type.
2. Rainstorms producing maximum intensities are mostly the result of violent convection.
3. The occurrence of thunder affords quite positive proof of the existence of suspension storage, and the sudden precipitation of such storage is probably a usual cause of high rain intensities for short intervals of 5, 10, or 20 minutes.
4. High rain intensities for longer intervals are probably due to storm gusts or pulses.
5. High rain intensities for long periods are result of general cyclonic conditions.

The writer has not attempted in this article to give definite formulæ of general applicability for the expression of the relation between rain intensity, duration, and frequency. It is hoped that the results given will suggest and encourage further study along similar lines, such as may afford a more complete basis for generalization.

The requirements for a rain intensity formula based on investigations thus far made may be stated as follows:

(1) It should indicate a finite intensity for zero duration and for the minimum exceedance frequency.

(2) For a given duration the rain intensity should approach a finite maximum or limiting value as the exceedance interval increases.

(3) The maximum or limiting value should decrease as the duration interval of the rain increases.

(4) A single general type of formula should be applicable ovel extensive geographic areas and to regions varying in amount of seasonar precipitation and thunderstorm frequency.

(5) The formula may contain constants whose values in turn can be expressed either in terms of unit rain intensity, thunderstorm frequency, or total precipitation during the thunderstorm season.

(6) The form of expression should be such as to give the required intensity in terms of duration and exceedance interval, so that when the constants are known for a given location intensities of varying duration, but of the same frequency, can be determined directly on the one hand, or intensities of the same duration, but of varying exceedance intervals, can be obtained directly on the other hand."

The paper affords an admirable example of one of the points where the engineering profession and the science of meteorology meet; indeed, where meteorology is indispensable.—*C. L. M.*